Comprehensive Residual Stress Profiles for a Range of Weld Geometries and Materials

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1. Introduction

When components are joined together by fusion welding, residual stress fields are set up in the vicinity of the welded joint due to the high temperature gradients and plastic deformation in the vicinity of the weld. Since information is often not directly available on residual stress distributions, compendia with recommended (upper-bound) residual stress profiles for use in structural integrity analyses are included in R6[1] and BS7910[2].

In this study, the residual stress distributions typical of those due to welding and fabrication process were reviewed and the representative distributions for a range of weld joint types were examined. Stress profiles have been collated from data available in the public domain for various types of weld geometries[3].

Linear elastic stress intensity factors (SIFs) have been determined using finite element analysis in conjunction with the superposition method. The results were compared with the SIFs obtained using the stress distribution recommended in the assessment procedures R6 and BS7910.

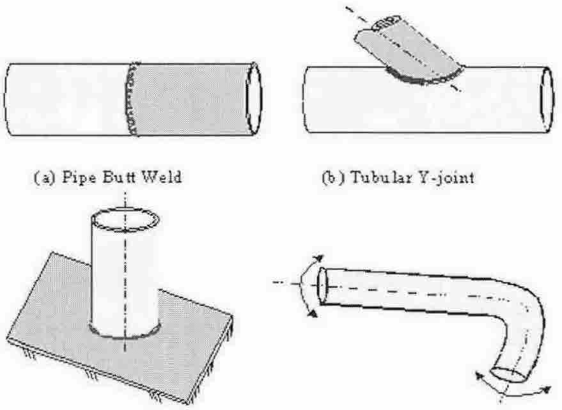


Figure 1. Schematic Diagrams of the Geometries Considered

2. Welded Joint Types

The weld geometries covered in this work are a pipe butt, pipe on plate, tubular Y-joint, tubular T-joint and a T-plate. Fabrication induced residual stresses due to a cold bending of pipes were also examined in this study; due to the inhomogeneous plastic deformation during bending a residual stress distribution which is established in the pipe. The measured data covers a range of conditions such as materials, measurement methods, plate thickness, weld heat input and boundary restraints. The materials included in the present geometries are ferritic, austenitic, C-Mn and Cr-Mo steels. The measurement methods used include neutron diffraction, X-ray diffraction, hole drilling and sectioning, block removal, trepanning, slotting and hole drilling.

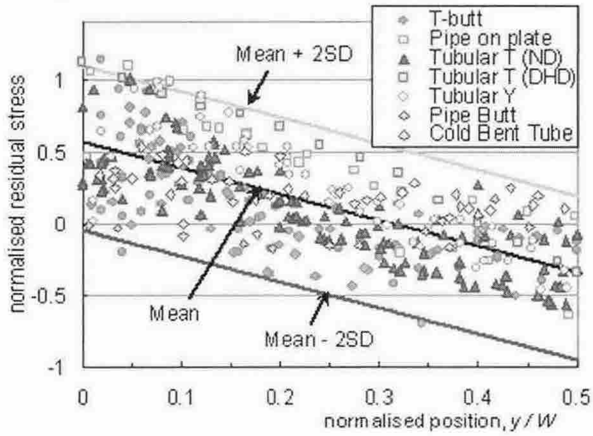


Figure 2. Transverse Residual Stresses for a Range of Welded Goemtries

3. Collection of the Measured Residual Stress Data

Data from the geometries described has been compared and is presented in Fig. 2. In Fig. 2 the transverse residual stresses for a range of geometries and materials normailised with their respective yield stresses are included. It may be seen that when the measured data are considered for up to $y/W = 0.5$ (half of specimen thickness), the stress distributions are represented well using a straight line. The region of interest for a life assessment is the short crack region starting at the surface and therefore $y/W=0.5$ is usually well beyond the safety margins that will be considered in any life assessment procedure. In addition for larger crack lengths there will be a redistribution taking place and the initial measured redistribution may become an inappropriate measure for the remaining net-section.

4. Statistical Analysis

It can be seen that all the normalised residual stress data (□□□$_y$□ can be conveniently descried by a linear regression line which contains a wide scatter. The variability of the data can be attributed to the differences in the geometry and materials as well as to a great extent to the scatter in the measurements of the residual stresses which in some cases could be as much as ±30%. Given the wide variability it would therefore be feasible to simplify the data to a linear relationship as shown in Figure 2 and to treat the data statistically.

The normalized linear mean line, for all the data, shown in Fig. 2 is given by:

$$\hat{\sigma} = -1.815x + 0.571, \qquad (1)$$

where $\hat{\sigma} = \square / \square_y$ and $x = y/W$.

The form of Eqn. (1) indicates that the normalised mean curve is composed of a membrane (uniform) stress component of approx. 0.57 and a bending (linear) stress with a slope of approx. □1.82. The degree of conservatism or otherwise, in estimating the SIF for the T-plate and tubular T-joint geometries, using a linear fit of this type, has been examined in a previous work[5].

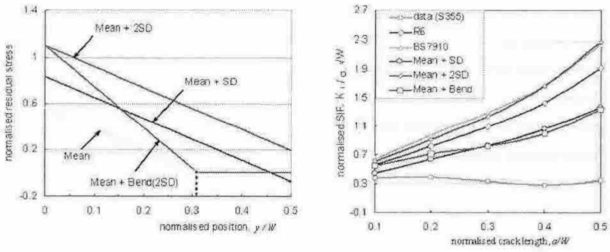
5. Results of the Analysis

As shown in Fig. 2 the present residual stress profiles are case specific and based on a shift in the membrane stress above the upperbound of the measured data. However it is possible to define a generic stress profile in terms of a linear shift in the mean line of the data and/or a shift in the bending stress based on the statistical data of all the data shown in Fig. 2. A sensitivity analysis of the SIFs using changes in the membrane and bending stresses with respect to the average linear fit of Eqn. 1 was conducted. Figure 3(a) shows the combinations of stresses used in the analysis. The linear fits of 'mean + SD (standard deviation)', 'mean + 2SD' and 'mean +2SD bend at the surface' was carried out.

The SIFs for the R6 and BS7910 distributions and the three potential stress distributions are shown in Fig. 3(b). The figure shows that the SIFs from the BS7910 distribution and the 'mean + 2SD' are almost identical and the most conservative, The R6 line the 'mean + SD' and 'mean + bend' line are the next most conservative. In Fig. 8, the SIFs obtained using the data from the Grade S355 T-plate are compared with the other five distributions. It should be noted that the 'mean + SD' and 'mean + bend' lines give better results than the R6 and BS7910 lines although they were derived from the dataset shown in Fig. 4 covering a range of weld geometries.

6. Conclusion

In this study, a review of the residual stress distributions for a range of welded joint types as well as cold bend tubes and pipes consisting of a range of steels has been carried out.



(a) Mean+Bend lines (b) SIFs

Figure 3. Definition of Profiles and the Corresponding Stress Intensity Factors

Based on the experimentally measured data of the wide range of components considered a set of comprehensive transverse linear residual stress profiles have been proposed which give satisfactory conservative estimates for the calculation of linear elastic stress intensity factors across various thicknesses of the range of component looked at. The SIF estimates using the present profiles for the T-Plate are shown to be less conservative when using the residual stress distribution profiles from the current procedures of R6 and BS7910.

Calculation of the SIF using the linear profile showed that the residual stress profile of 'mean + SD' and 'mean + bend' gave less conservative values with a reasonable conservatism both for the T-plate and tubular T-joint.

Acknowledgements

This study was supported by the Korean Ministry of Science & Technology through its National Nuclear Technology Program.

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